



SPIE ALP 2026 eBeam Initiative Luncheon Aki Fujimura, CEO, D2S, Inc.

Only Entirely Curvilinear Masks are Entirely Manufacturable Masks

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1982-1985

Digitalization begun

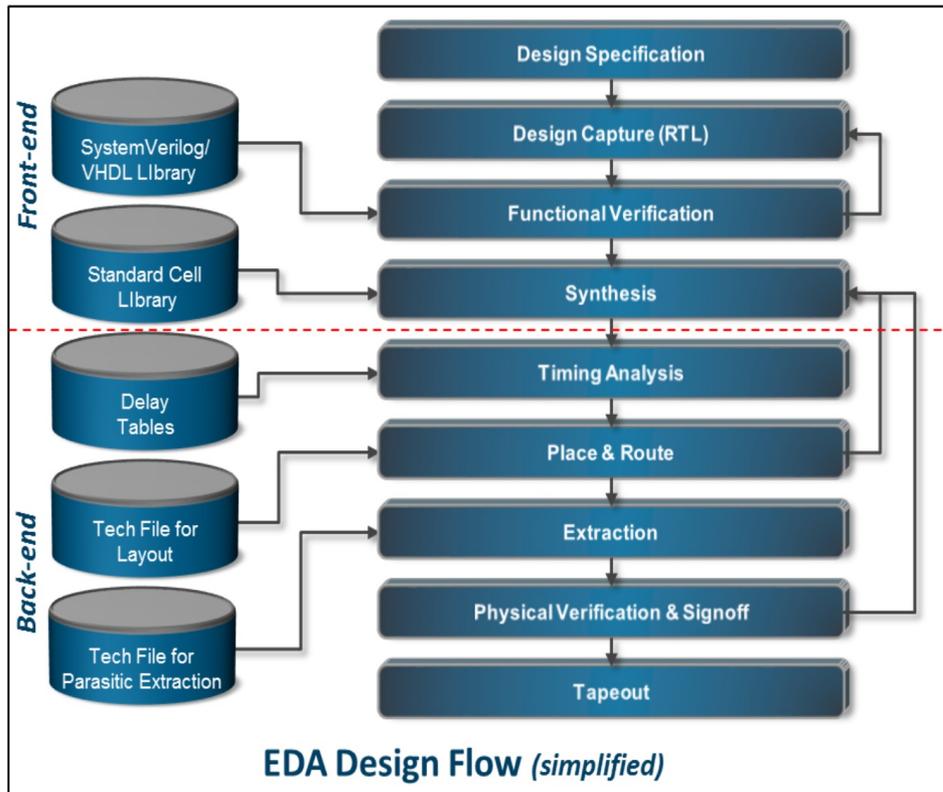


Thriller (1982), Epic Records. Cover photo by Dick Zimmerman



1980s was also the Decade of Automated Design

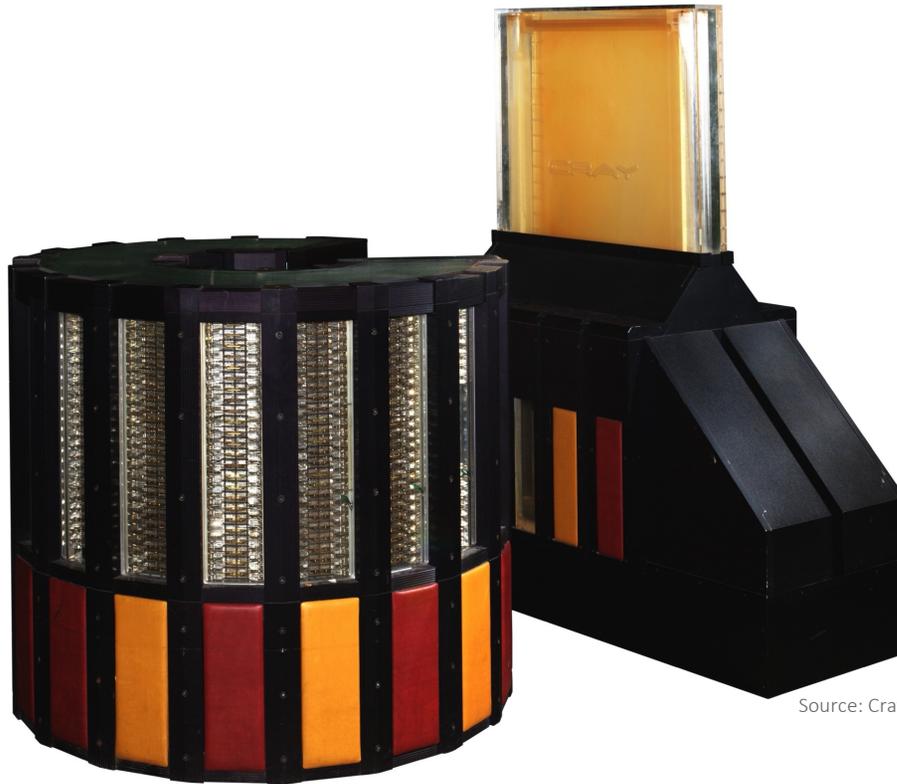
The basic scheme of automated design was set then



- Fully synchronous design
 - Verilog and VHDL
 - Logic simulation and synthesis
 - Scan-based test
 - Timing analysis and assurance
- >2 Layers of Metal
 - Over-the-cell routing
 - LEF, DEF, ECO...
- Design rule checking
 - Basis for mask rule checking later
- Workstations and ISVs with TBLs*

We Were Computationally Limited Back Then

IBM 3090: 30 MIPS, 50 MFLOPS, 126GB disk, 128MB RAM, 100KWatts, \$20M



Source: Cray



Source: IBM

History is Repeating Itself

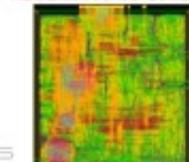
1975-1985 : Manhattan

EDA Transitioned to Workstations in the 1980's
Computing schemes needed to run on these machines

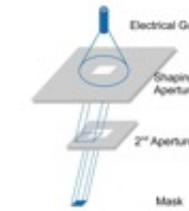



Cray-2	64 bits	1.9 GFLOPS	256MB	20-50GB	150-300KW	\$30M
IBM 3090	32 bits	30 MIPS	128MB	126GB tape	200KW	\$30M
DEC vVAX II	32 bits	1 MIPS	1-16MB	70-300MB	600-900W	\$60K
Sun 3/50	32 bits	4 MIPS	8-16MB	150MB	200-300W	\$12K

Computing Limited Chip Routing to Manhattan
Needed to break away from PCB-based routing schemes

At the Same Time, Mask Writing Went Manhattan, too
4X masks and commercial VSB writers arrived about 1985



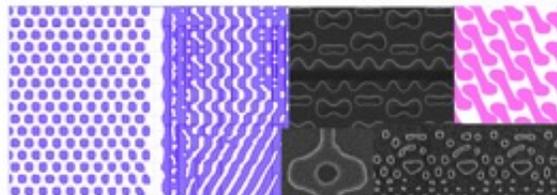

2007-2020 : Curvy

NVIDIA Ampere in 2020 Made GPUs Fast Enough
Jensen introduced GP-GPUs with CUDA in 2006



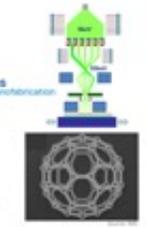
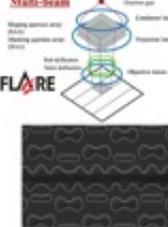
GPU Only	AMD (2005)	32 bits	37 TFLOPS	48GB	0 on GPU	300W	\$7K
	RTX6000B	32 bits	125 TFLOPS	96GB	0 on GPU	600W	\$30K
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	Difference		250M x FP	6,000x	600x in RAM		2x MORE

Now That Computing Isn't Limited
Entirely curvilinear masks are inevitable



Around 2016, Multibeam Writing Enabled Curvy
IMS' 2007 paper at BACUS became a huge success



EDA Transitioned to Workstations in the 1980's

Computing schemes needed to run on these machines

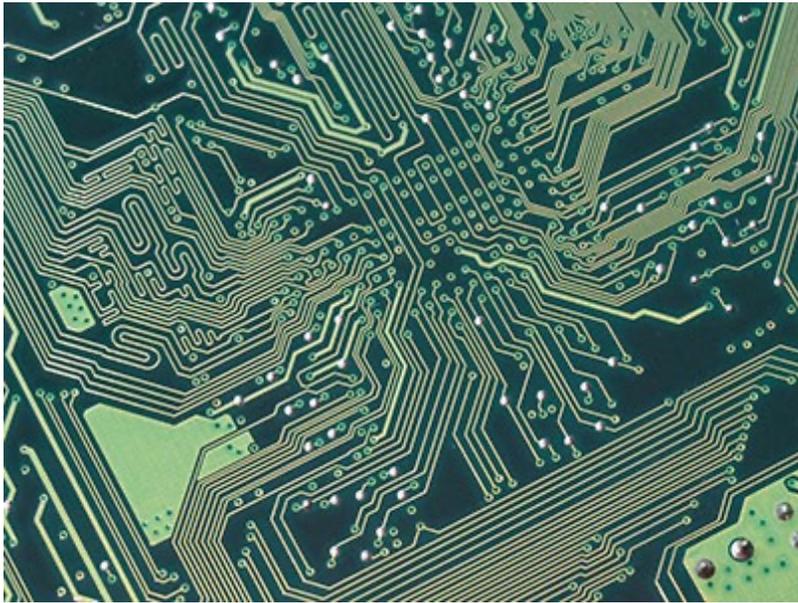


~1985

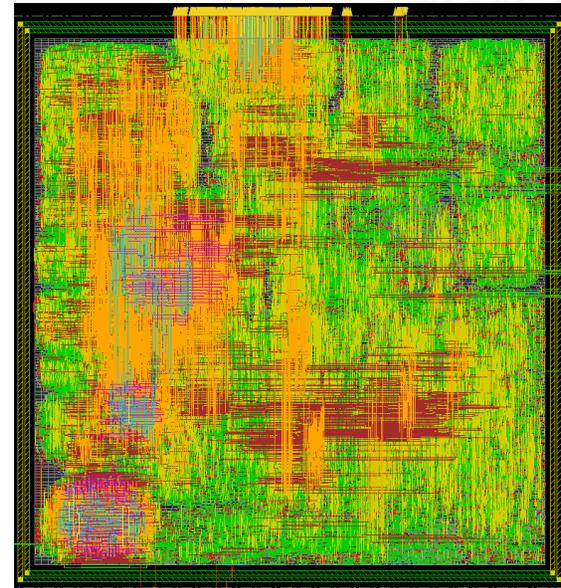
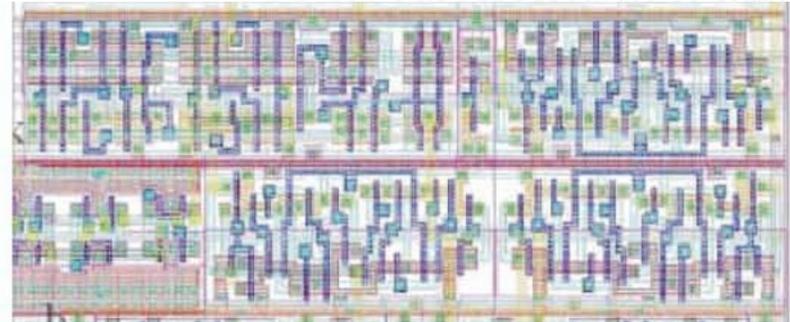
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Computing Limited Chip Routing to Manhattan

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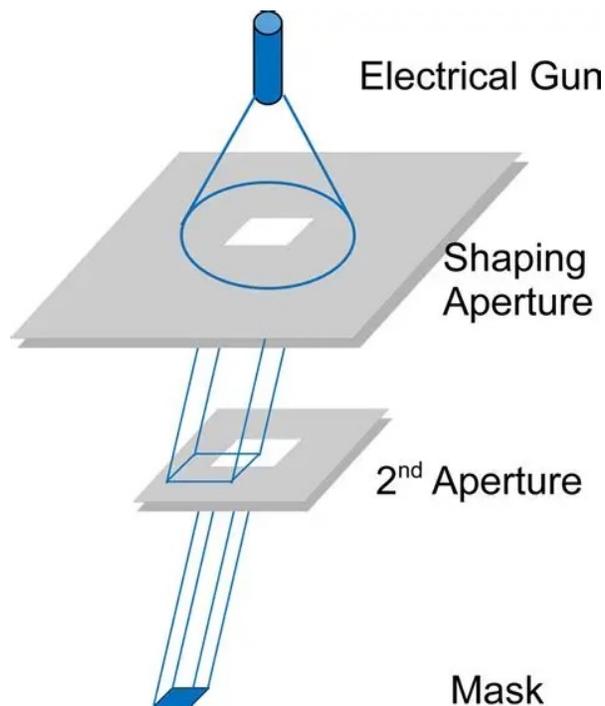
Source: ourpcb.com



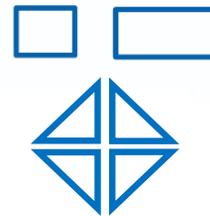
Source: Vladimir Stojanovic, course materials for 6.973 Communication System Design, Spring 2006. MIT OpenCourseWare

At the Same Time, Mask Writing Went Manhattan, too

4X masks and commercial VSB writers arrived about 1985



Source: University of Texas, Austin



VSB Basic Primitives



NuFlare's 2nd Aperture



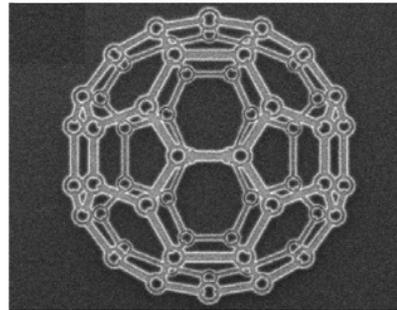
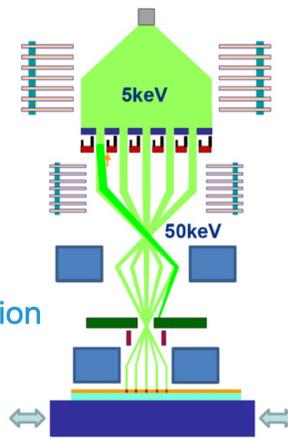
Around 2016, Multibeam Writing Enabled Curvy

IMS' 2007 paper at BACUS became a huge success

SPIE.
BACUS 2007

Conference 6730 • Room: Steinbeck Forum

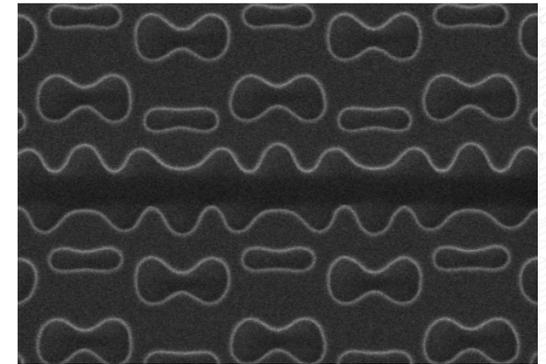
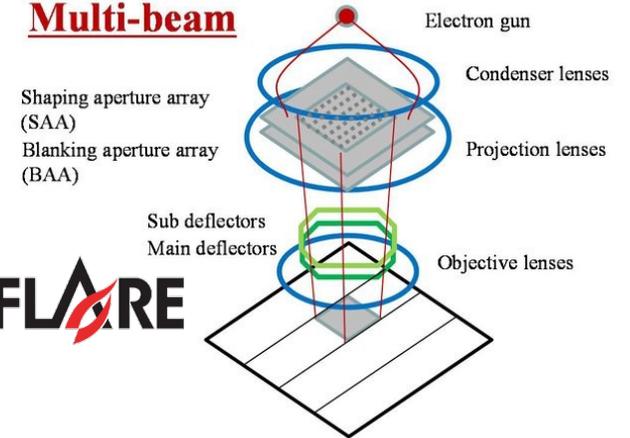
Thursday 20 September



Source: IMS



Multi-beam

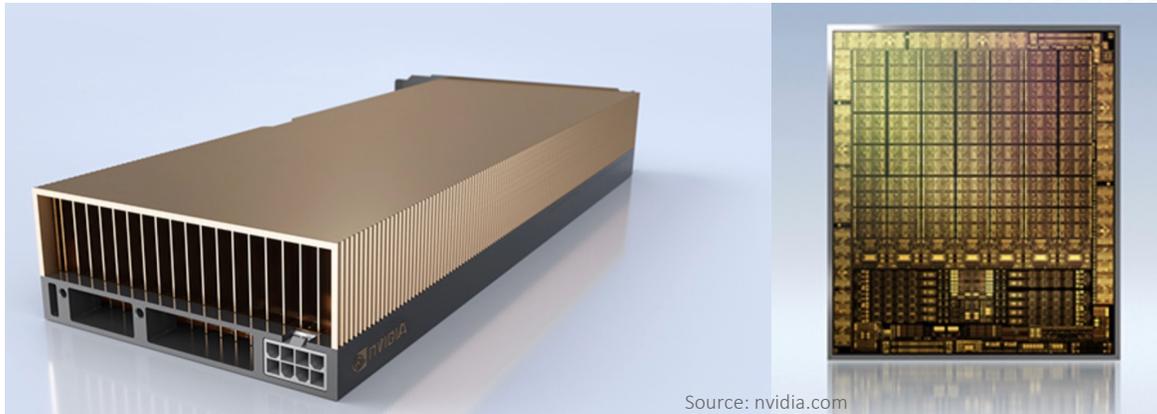


Source: NuFlare

9:40 am: **Projection maskless patterning (PMLP) for the fabrication of leading-edge complex masks and nano-imprint templates**, E. Platzgummer, H. Löschner, G. Gross, IMS Nanofabrication AG (Austria) [6730-108]

NVIDIA Ampere in 2020 Made GPUs Fast Enough

Jensen introduced GP-GPUs with CUDA in 2006



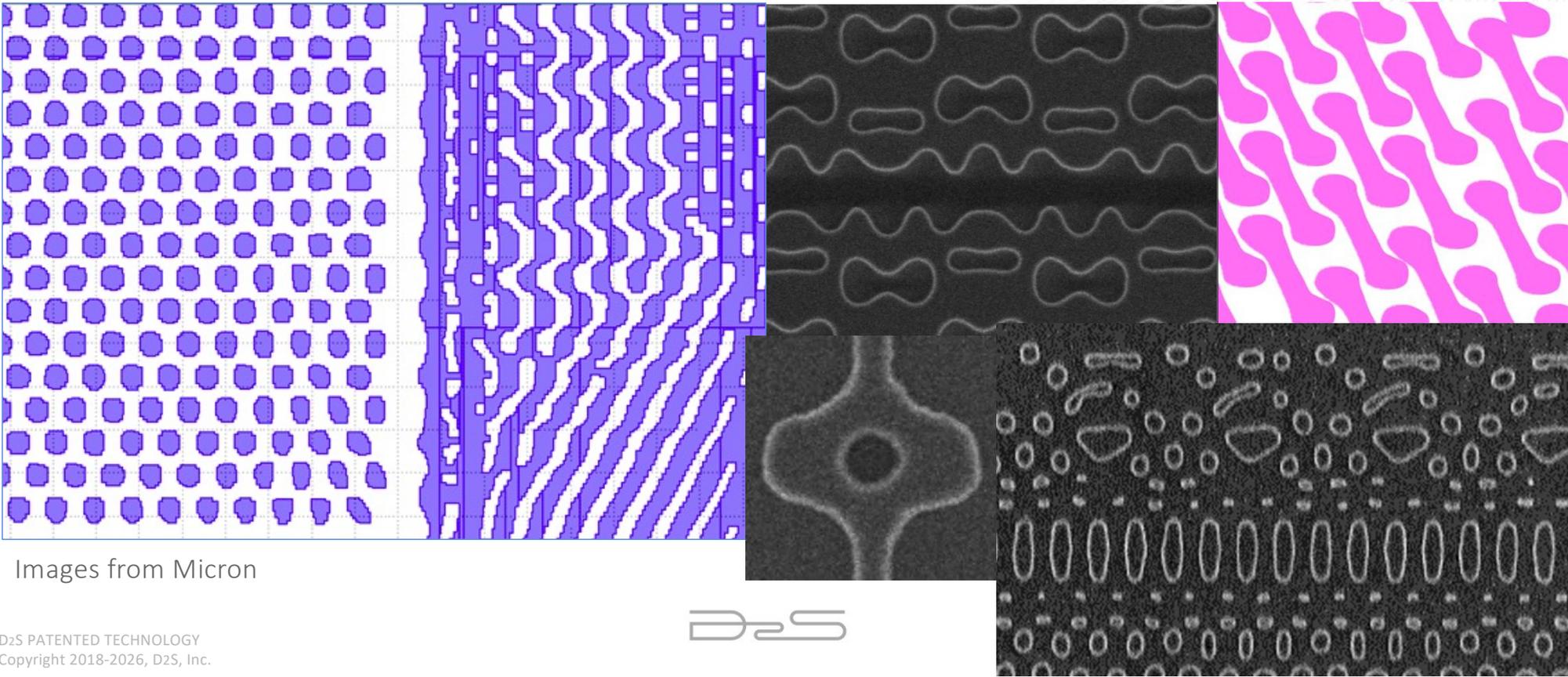
Source: nvidia.com

GPU Only

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Now That Computing Isn't Limited

Entirely curvilinear masks are inevitable



Images from Micron

Only Entirely Curvilinear Masks are Manufacturable

But not all curvy masks are entirely manufacturable masks

Curvilinear Masks Benefit

- Significantly larger process window
- Better NILS, better LCDU
- Computationally intensive
- Requires multi-beam mask writer

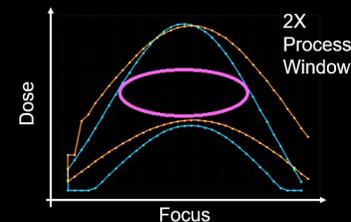
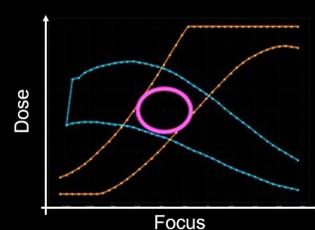
Manhattanized Mask



Curvilinear Mask



Process Windows, Two Features



micron | 13

Source: Micron

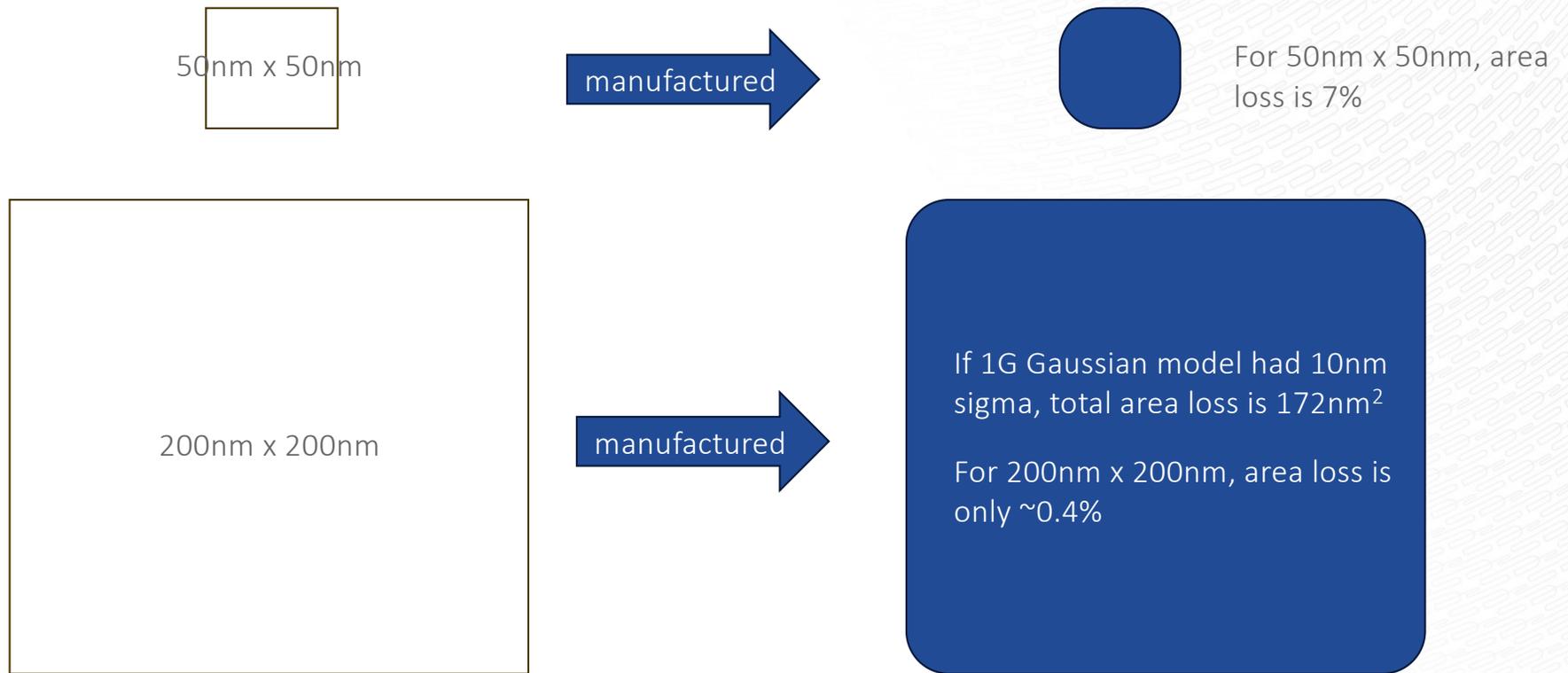
Four reasons for curvy masks

1. 2X Process Window
2. Manufacturable masks:
Ask for what you can get, and get what you asked for
3. Manufacturable masks:
Best area uniformity on mask for best wafer CDU
4. Enables Curvy Designs

Wafer Accuracy is About Area Accuracy on Mask

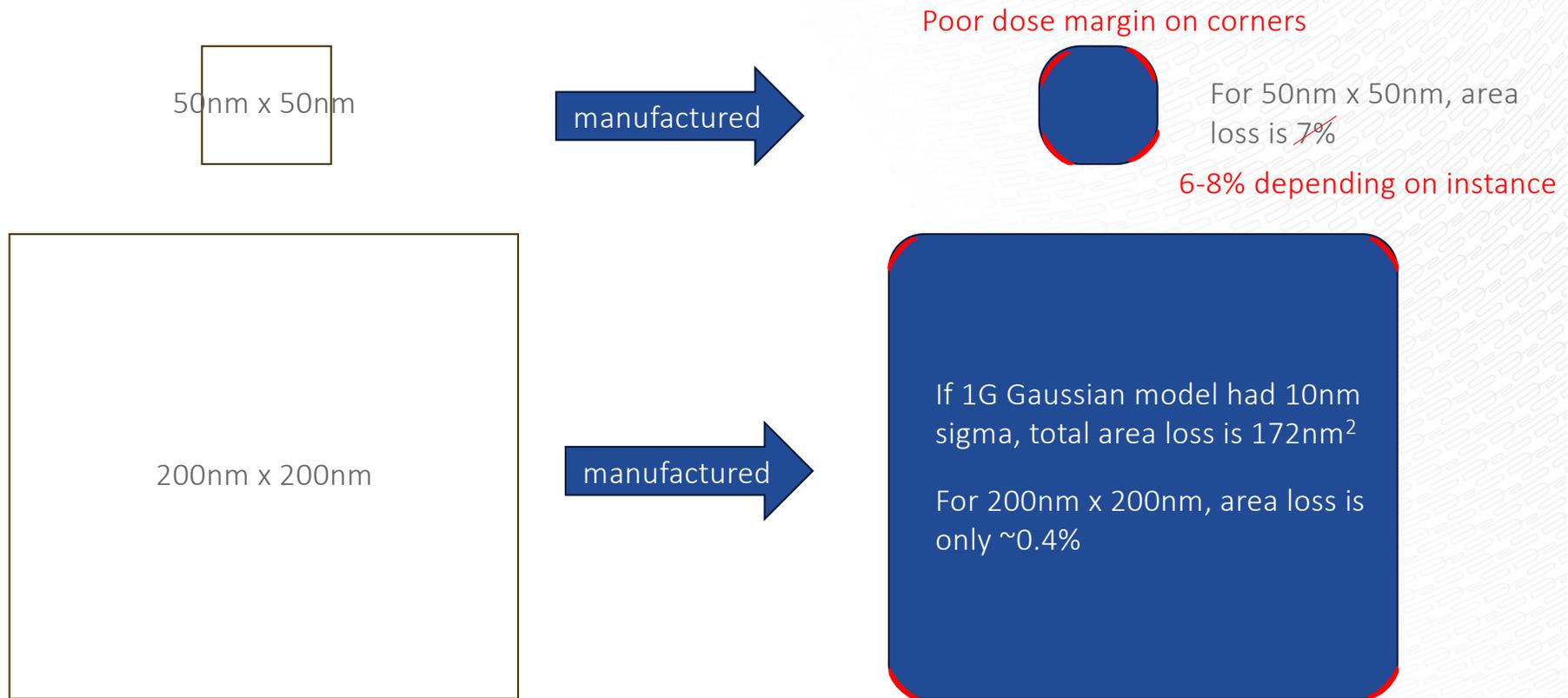
So smaller shapes we need to handle now can't be doing 1D on mask

This is already true for all decorated OPC masks before Curvy...



Unmanufacturable Shapes Always Have Bad Dose Margin

Instance-to-instance mask area uniformity is critical for wafer CDU

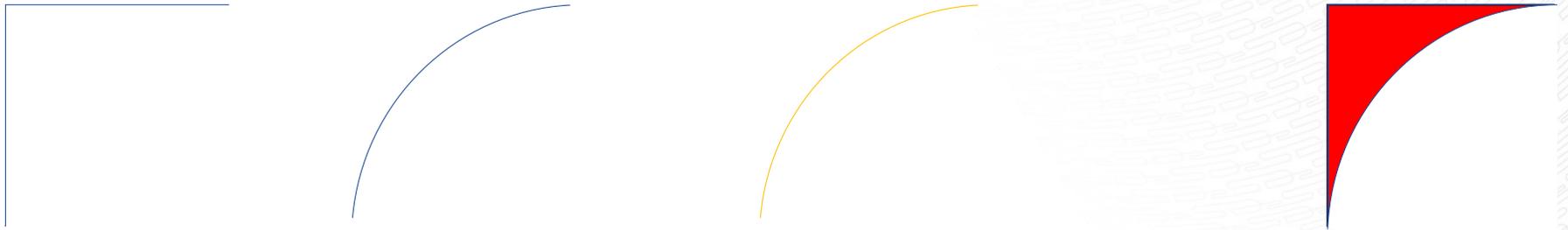


Much Better to Ask for What You Can Get

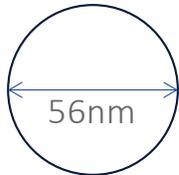
Instance-to-instance variation is critical for manufacturing

Trying to manufacture this and getting this has more variation than trying to manufacture this

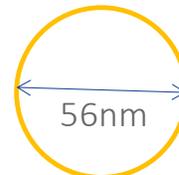
because the dose of **this area** changing +/-x% makes a big difference.



If you ask for what you can get...



You get better mask area uniformity and therefore, better wafer CDU



Ask for what you can get

And get what you asked for,

It will be manufactured as you litho simulated,

and with better mask area uniformity, and wafer CDU

DES